Ultra-low NOx ISX G (HPDI EGR) Project

Presentation to NGNGV Steering Committee July 2003

Powering the Planet - Protecting the Dream

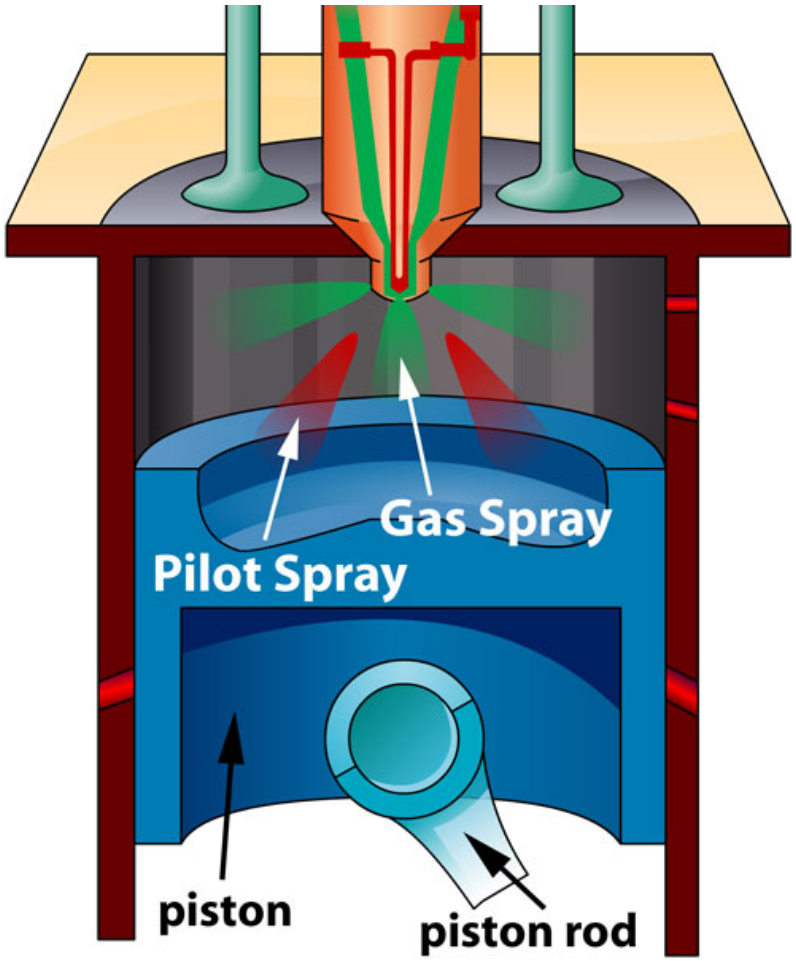
Background

- Project pre-dates Cummins Westport Joint Venture
- Cummins are NREL subcontractor
- Westport subcontractor to Cummins
- 2 year program that has enabled Cummins Westport ISXG 2004 product development
- Will form foundation of work for 2007 ISXG technology development
- Program completion expected fall 2003

Introduction

- Develop ISX ’02 Diesel EGR platform with Westport fuel system to meet targets of:
  - 0.5g/bhp-hr NOx
  - 0.1g/bhp-hr PM
  - >40% peak thermal efficiency
  - 450hp, 1650 ft-lbs rating, same torque curve as diesel
- The ISXG engine uses High Pressure Direct Injection or Westport-Cycle™ to achieve diesel-like performance and fuel economy

Pilot Ignited HPDI Process



- Small quantity of pilot diesel injected before natural gas to provide ignition
- Natural gas injected at high pressure at end of compression stroke in place of diesel fuel
- For automotive, high pressure natural gas is derived from pressurized of LNG
- Retains diesel cycle: high low-speed torque, efficiency
- Lower emission process

Task Schedule and Status

Task	1Q	2Q	3Q	4Q	5Q	6Q	7Q	8Q
1. Analysis	100%							
2. Engine Set Up and Commissioning	100%							
3. Diesel Baseline Testing		100%						
4. EGR Functionality and Baseline Testing		100%						
5. HPDI Baseline Testing			100%					
6. Preliminary Optimization				100%				
7. Oxidation Catalyst Sourcing and Testing				100%				
8. Optimization - Multi Variable				100%				
9. Hardware Improvement and Controls				100%				
10. Optimization and Calibration Refinement						70%		
11. Final Certification Tests								

- Program nearing completion but will be slightly extended from original work plan

Year 1 Accomplishments

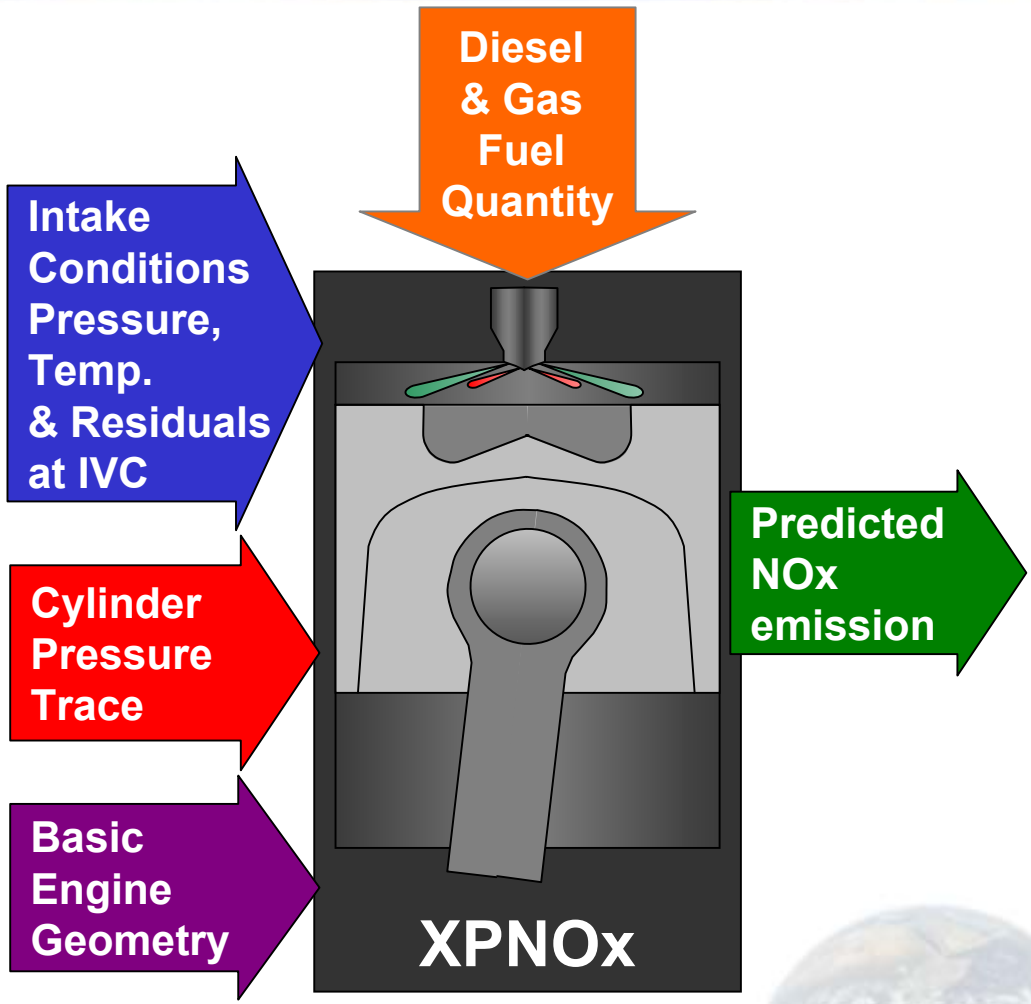
- Diesel EGR ISX installed at Westport
  - Compares well with Cummins results
- Built and validated NOx and performance prediction tools
- Up-fitted to HPDI system and demonstrated compatibility of technologies
- Undertaken preliminary optimization
- Approached 0.5g/bhp-hr levels at individual conditions
- Identified current EGR H/W limitations
- Planned oxidation catalyst and multivariable optimisation work

Year 2 Accomplishments

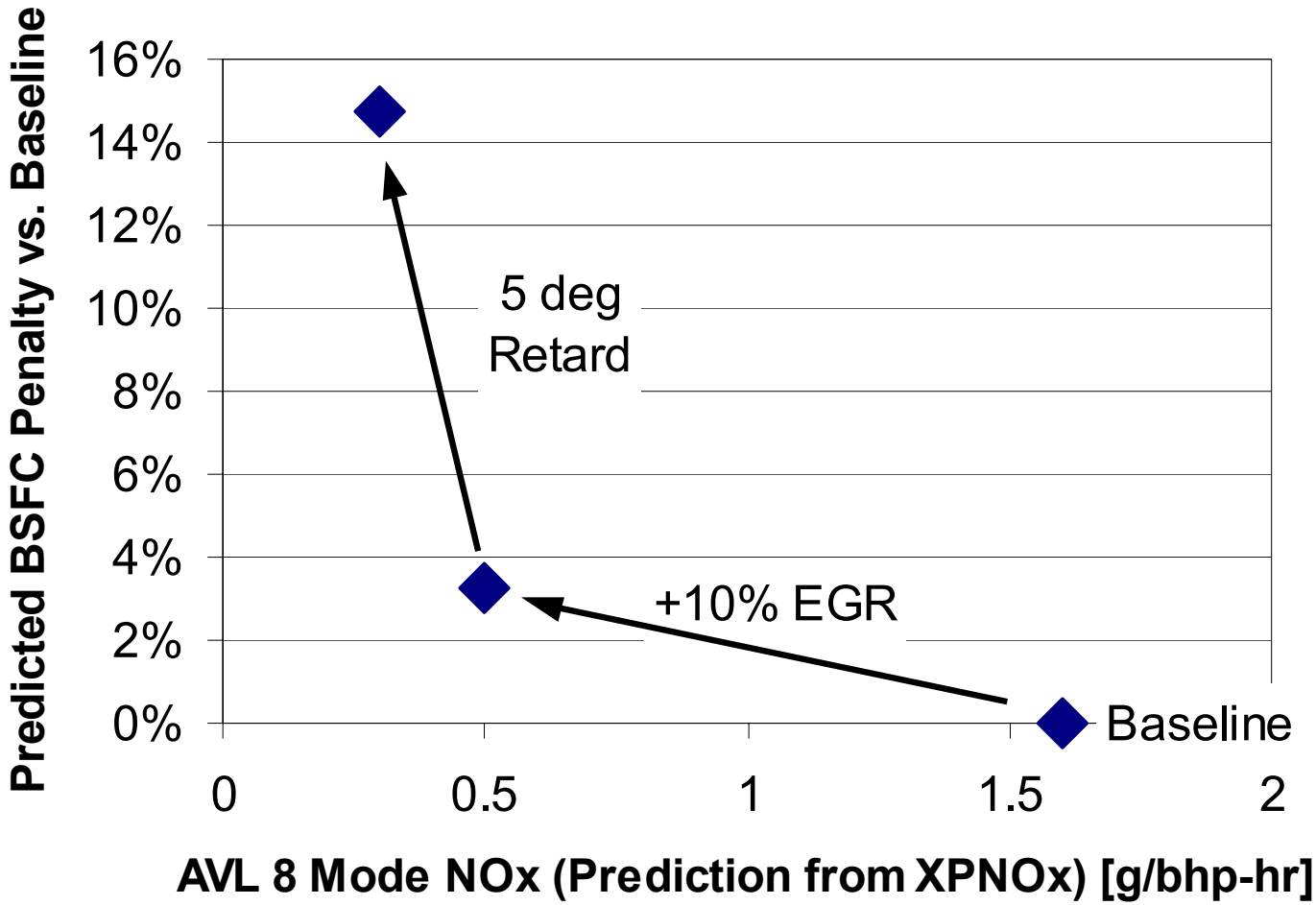
- Showed benefit of higher gas pressure (30MPa)
- Sourced and tested alternative oxidation catalysts
- Produced plan to 0.5g/bhp-hr NOx through analysis (smaller compressor trim, more cooling)
- Implemented turbocharger change
- Conducted multiple stages of design of experiments optimization of control levers
- Upgraded to final prototype engine
  - ISX ’02 production engine
  - integrated controls and increased EGR cooling
- Characterized EGR distribution
- Continued optimization of control levers

XPNOx Model

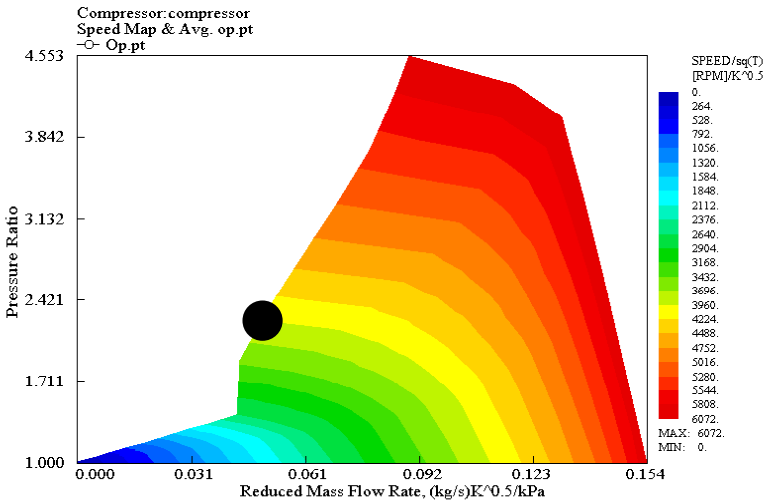
- In-house multizone model
- Inputs from measured data (diagnostic) or predicted data (predictive)
- Separate zone is created representing fuel consumed during each crank angle.
- Calculates development of NOx during combustion
- Combustion assumed stoichiometric
- Extended Zeldovich mechanism is used in each burned zone for a period of one “turbulent mixing time” after burning.

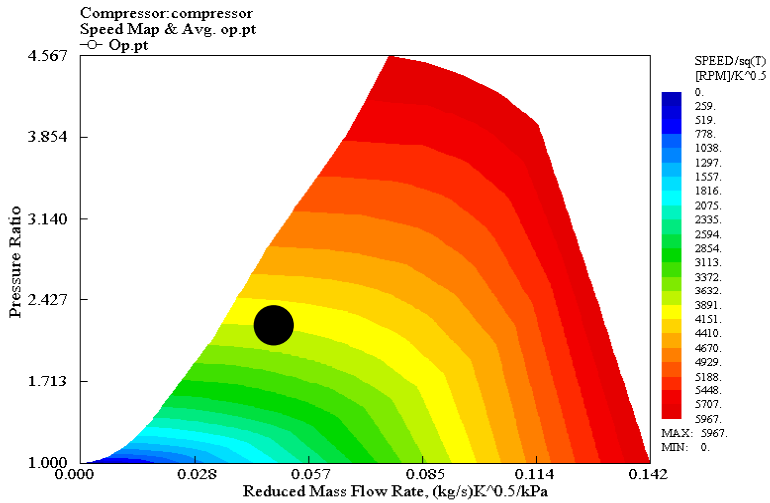


0.5 g/bhp-hr NOx Recipe From Analysis



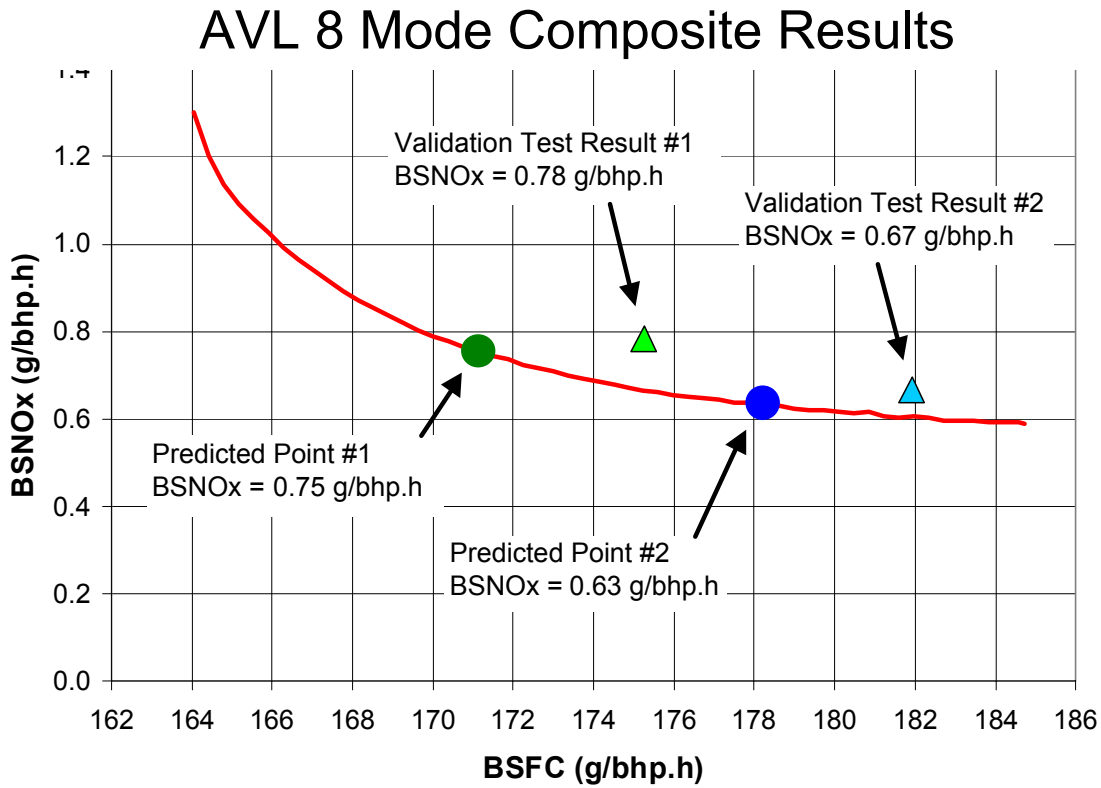
Smaller Compressor Trim





- Standard compressor suited to ratings >>500hp
- Some margin to tailor for 450hp application
- Smaller trim provides increased surge margin at AVL mode 4

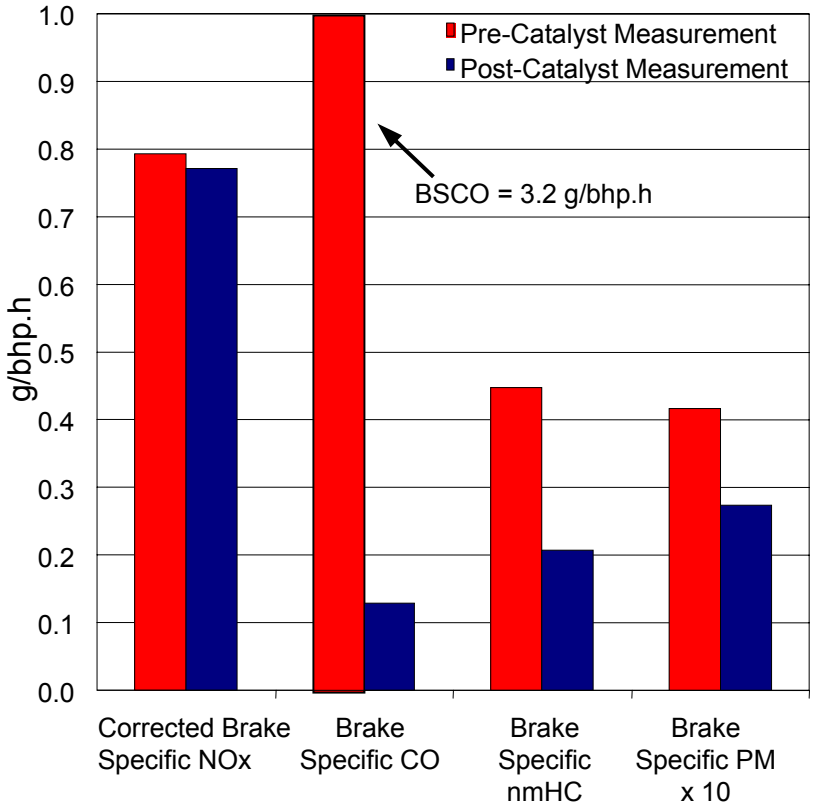
NOx Efficiency Trade Off From Tests

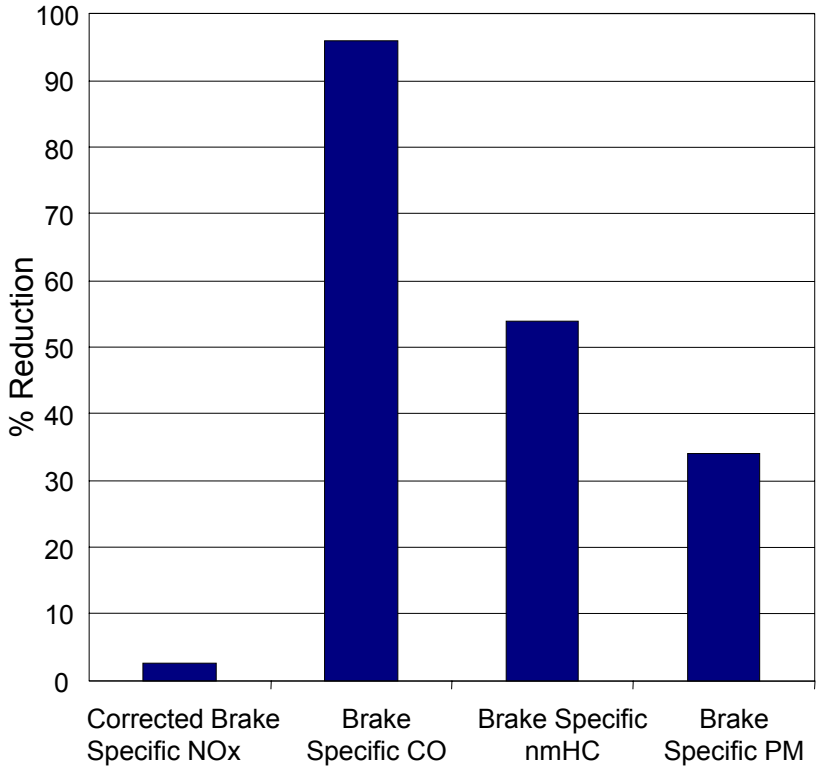


- Engine has 6 independent control levers
- Results from first round of multi-variable optimization

Impact of Oxidation Catalyst

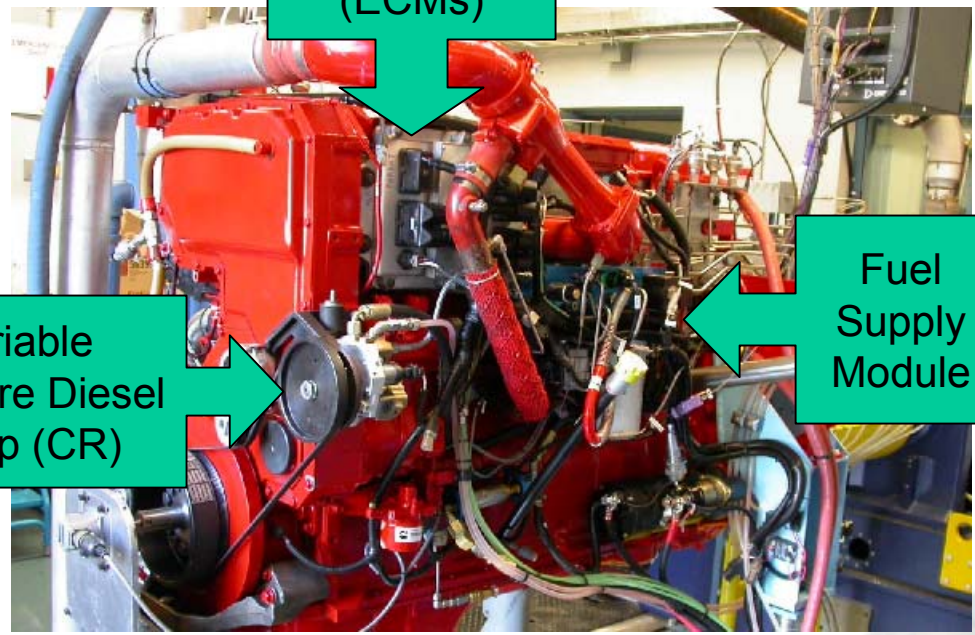
AVL Cycle Composite Weighted Emissions





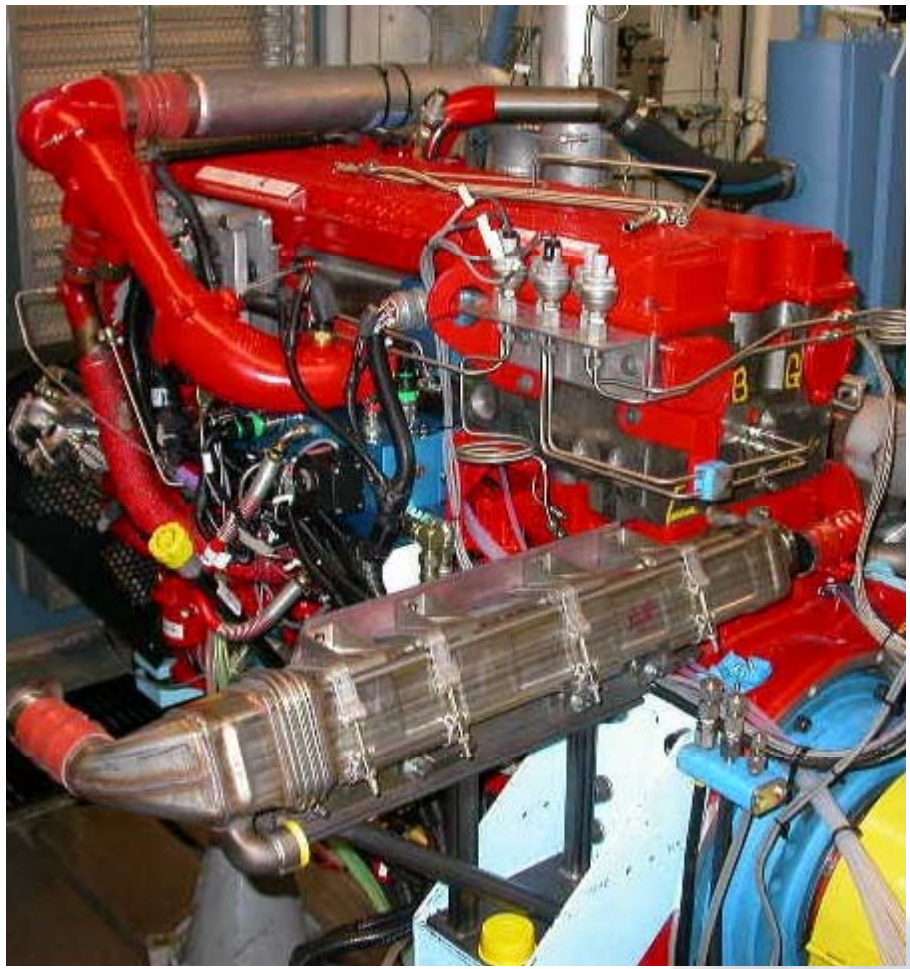
- Oxidation catalyst effective for CO, NHMC and PM reduction

Prototype Engine & Test Cell

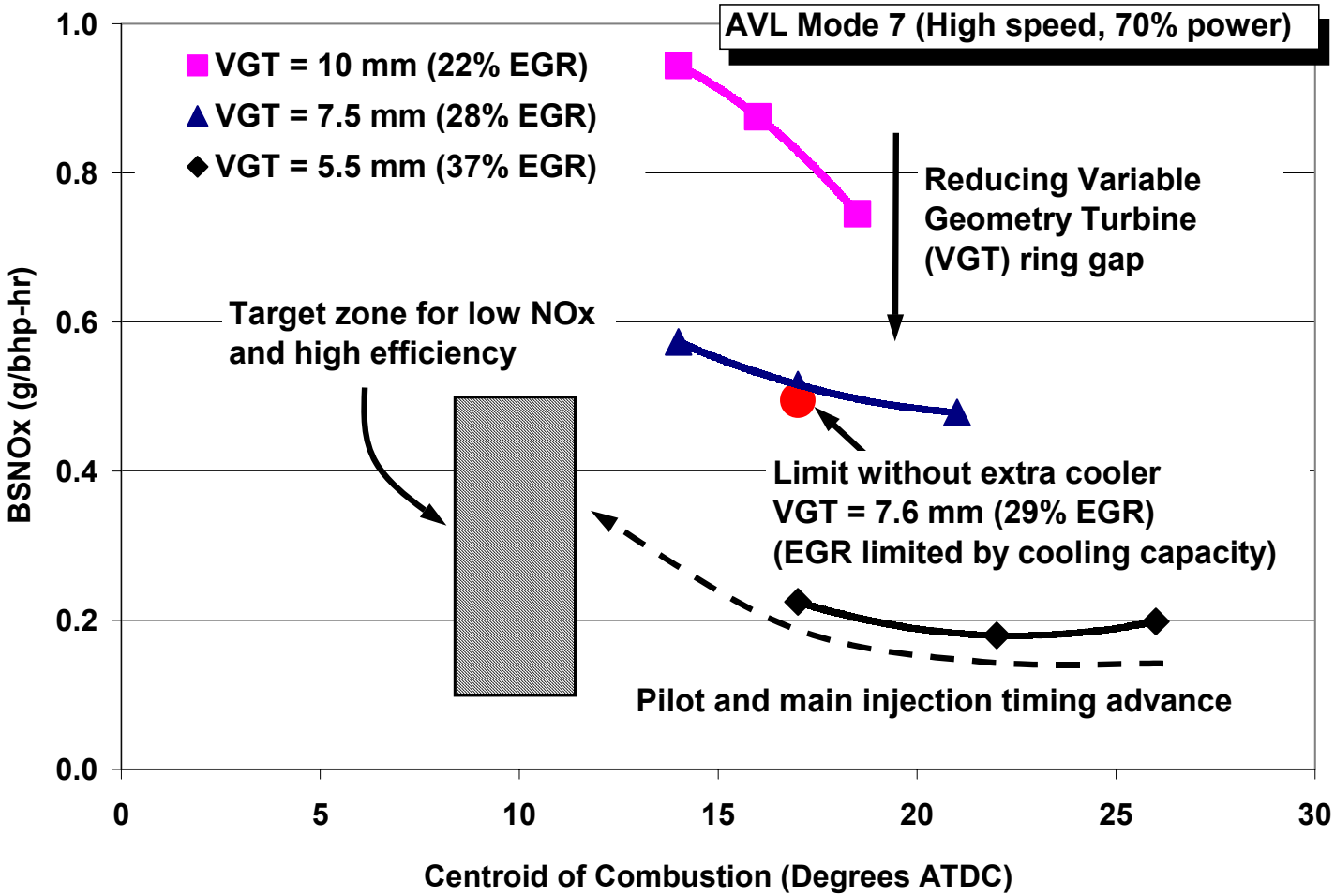


Additional EGR Cooler

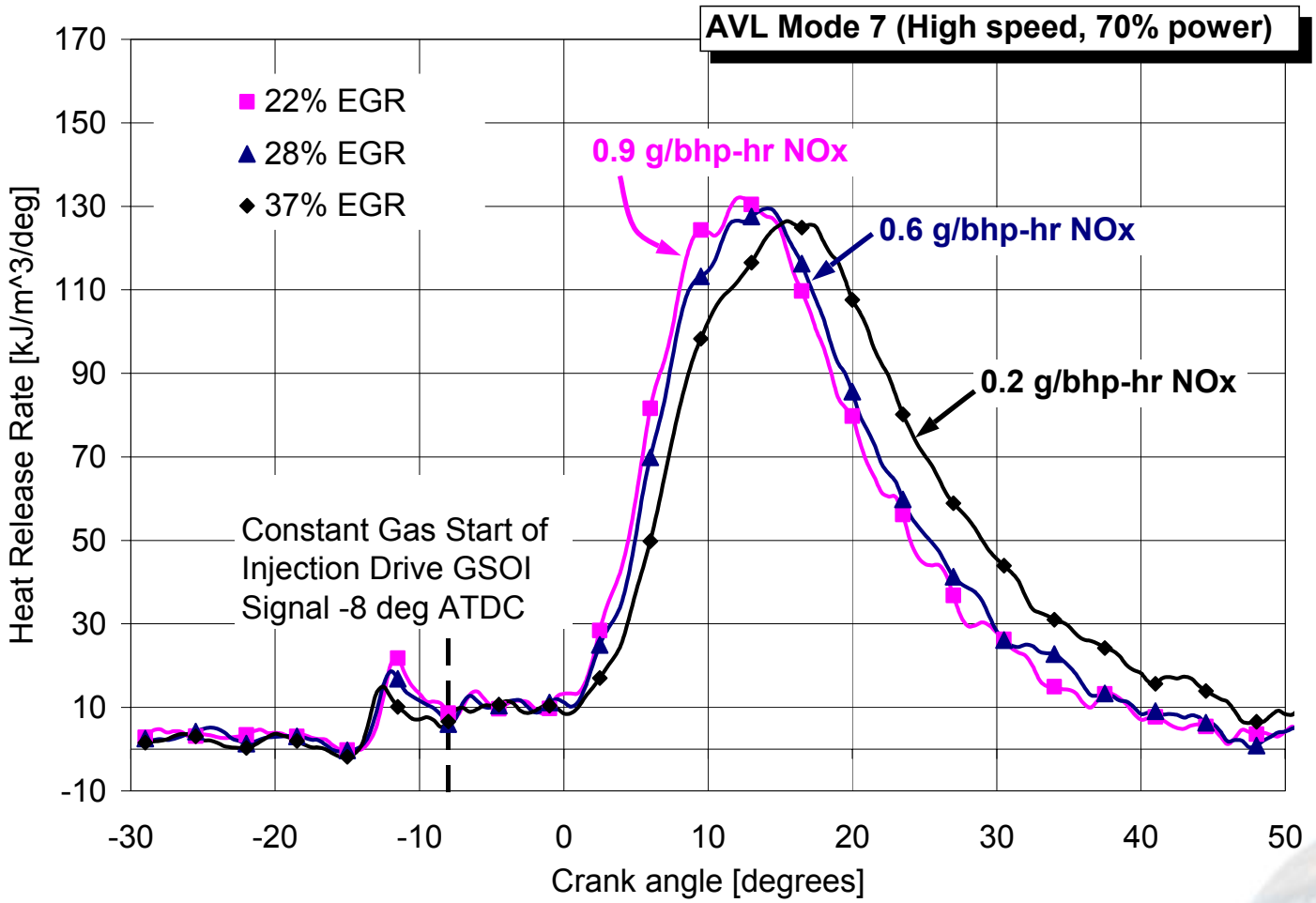
- Required to allow higher EGR rates
  - charge temperature limits
- Also lower NOx via cooler charge
- Additional ISX ’02 cooler
- In series with existing cooler
- Location / packaging for test cell purposes only
- Likely production solutions
  - enlarged single cooler or
  - smaller additional cooler



Impact of Additional Cooling



Ultra-Low NOx with Efficient Burn



Current Status

AVL 8 mode Cycle Weighted Emissions	Without Extra EGR Cooler	With Extra EGR Cooler	With Extra EGR Cooler and more EGR at modes 7 and 8	*Program Targets (FTP Test)*
Corrected Brake Specific NOx	0.77 g/bhp.h	0.69 g/bhp.h	0.53 g/bhp.h	*0.5 g/bhp.h*
Brake Specific nmHC	0.4 g/bhp.h	0.51 g/bhp.h	0.56 g/bhp.h	---
Brake Specific CO	2.57 g/bhp.h	3.21 g/bhp.h	6.16 g/bhp.h	---
Brake Specific HC	2.98 g/bhp.h	4.19 g/bhp.h	4.48 g/bhp.h	---
Brake Specific CH4	2.49 g/bhp.h	3.55 g/bhp.h	3.77 g/bhp.h	---
Brake Specific PM	0.03 g/bhp.h *	*N/A*	*N/A*	*0.1 g/bhp.h*
Peak Thermal Efficiency	39.9%	39.8%	39.8	*>40%*

** Results with oxidation catalysts reported in progress report No. 6*

- With additional cooler and some re-optimization potential to achieve program target shown

Leverage from Product Dev't

- Latest base hardware derived from ISXG product development program
- Product development program has developed the revised controller hardware
- Transient development work is on-going and making good progress
- Ultra-low NOx transient development will be based on calibrations to be used at Norcal field trial location

Summary

- Are now operating on the latest prototype hardware in close collaboration with ISXG product development team
- Demonstrated as low as 0.53g/bhp-hr NOx
- Tests are supporting earlier estimates of around 4% fuel penalty to reach lower NOx levels
- In final round of design of experiments optimization
- Preparing for transient development and demonstration

Outlook

- Project has already lead to technology in process of certification
  - 2004 ISX G (1.2g/bhp-hr NOx, 0.03g/bhp-hr PM)
- Considering follow-up plans for 2007 requirements
  - Desired outcome is product improvement to 0.5g/bhp-hr NOx level with simple catalyzed PM controls